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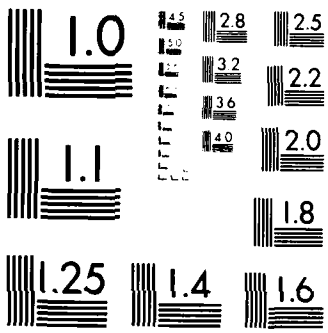

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On the Use of X-Band CW Nanosecond Airborne Radar for Terrain Profiling

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Space Sensing Branch
Space Systems and Technology Division

June 25, 1985

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Terrain profile sensed by a 10 GHz X-band airborne nanosecond radar has been compared against the terrain profile sensed simultaneously by a pulse laser profilometer. Several facts can be observed from a series of inter-comparisons between these two profiles. First, under the condition of comparable sampling intervals, the terrain profile sensed by radar is almost the same as that sensed by the laser profilometer except radar sensed profile does not contain information of narrow and tall objects above the ground surface. Second, a radar range resolution finer than 4 nanoseconds and a better algorithm on return waveform analysis for identifying narrow and tall objects in addition to the ground surface are going to improve accuracy and precision of radar's capability in terrain profiling. Third, for a short flight track, the removal of the effects on radar range measurements due to aircraft motion cannot be achieved without knowing three ground surface elevations whose locations are well separated along the flight track. Last, the limit at which radar range tracking circuitry loses its lock and, thus, its ability in resolving range is higher for aftside range slopes than for foreside range slopes.

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CONTENTS

ON THE USE OF X-BAND CW NANOSECOND AIRBORNE RADAR FOR TERRAIN PROFILING

I. INTRODUCTION

When a continuous wave (CW) pseudo random noise (PRN) coded nanosecond radar system is used for terrain profiling, several system parameters can be used to characterize its performance capability for terrain resolution. These radar system parameters are range resolution, number of returns used in averaging for optimal signal-to-noise ratio, equivalent pulse repetition rate (sampling rate), width of range detection window, and range tracker rate. For an off-nadir looking radar system there is, of course, the additional important system parameter of look angle. Let us limit our discussion to a nadir-looking radar system.

In this report one terrain profile sensed by a 10 GHz X-band airborne nanosecond radar will be compared against the terrain profile sensed simultaneously by a pulse laser profilometer for several radar system parameters. Based on results of this comparison, recommendations for an optimal special-purpose terrain profiling airborne radar are developed.

II. RADAR SYSTEM PARAMETERS

System parameters which characterize the performance of a terrain profiling airborne radar are range resolution, equivalent pulse repetition rate, number of returns averaged, width of range detection window, and range tracker rate. The physical meanings of the system parameters and their roles in the determination of terrain resolution are briefly described in the following.

1. Radar Range Resolution

The radar range resolution, τ, in time units for a CW PRN coded radar is defined as the length of time the internal code, controlling the timing of 180° phase shifts of the continuous wave train, remains unchanged. Correspondingly the physical range resolution is $C\tau/2$ where C is the speed of light. With the radar antenna altitude, H, and range resolution known, the radius, r, of the radar footprint on a flat terrain can be computed as

$$r = \sqrt{(C\tau/2)\ (2H + C\tau/2)} \sim \sqrt{C\tau H} \qquad (1)$$

where C is the speed of light, 3×10^8 m/sec. However, at low altitude, radar antenna beam width becomes the limiting factor, especially for range resolution of four nanoseconds. Reflection of radar signals from the surface within the footprint forms a return waveform. The reflected energy from the surface to the antenna is almost entirely from the vicinity of the nadir and decreases very rapidly as the illuminated area spreads outward

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from the nadir to the edge of the footprint (Horan and Choy, 1984). In other words, radar's basic spatial resolution cell has an effective dimension smaller than the dimension of the footprint πr^2 where r is given by Equation (1).

2. Equivalent Pulse Repetition Rate

The number of equivalent radar pulses sent out per second is called the equivalent pulse repetition rate. The quotient of the radar platform speed $|\vec{v}|$ to this equivalent pulse repetition rate, p, gives the basic sampling distance Δs of successive radar signals on the ground surface as

$$\Delta s = |\vec{v}|/p \tag{2}$$

where $\vec{v}$ is the velocity of the radar platform. From Equation (2), it is easy to see, that rough-terrain profiling requires higher equivalent pulse repetition rate or lower radar platform speed than those required by smooth-terrain profiling because Δs should be small enough to accommodate the sharp "ups and downs" characteristic of the rough terrain.

3. Number of Returns Averaged

Because system noise, usually of white noise type, is commonly associated independently with radar transmitting and receiving systems, the reflected signals presented as return waveform contain noise. If the radar system is properly calibrated to account for system noise, it is possible to remove its effects on the return waveform by an on-board pre-processor or off-board post analysis. An alternate technique using statistical averaging is routinely used for reducing these effects in the absence of proper calibration. Both techniques increase the signal-to-noise ratio of the radar system.

Because both the noise and information components contained in each individual return waveform are mutually independent, statistical averaging of return waveforms can reduce noise level as well as variability in information presented. This type of averaging is meaningful only if the radar target does not change its characteristics within the period during which the return waveforms are collected for averaging. If the radar system noises are known to be non-symmetrically distributed, the statistical averaging of return waveform alone is sometimes considered inadequate for deducing the desired result without the removal of noises from each individual return waveform.

There is one drawback in using a radar system in terrain profiling. If the statistical averaging of return waveforms has to be used to process the data, i.e., the basic sampling distance Δs in Equation (2) is increased to $n \bullet \Delta s$ where n is the number of return waveforms used in averaging. Let us call $n \bullet \Delta s$ the sampling distance, s, and is given, from Equation (2), as

$$s = n \bullet \Delta s = n|\vec{v}|/p \tag{3}$$

Since n measurement samples are averaged for an average sample, terrain features whose spatial scale is smaller than s cannot be resolved by radar.

4. Width of Range Detection Window

Functions of the radar receiver are controlled by codes as well. Based upon the distance from radar platform to surface and the equivalent pulse repetition rate these codes determine when the return signals to the receiver should be recorded so that unwanted signals or interference will not be recorded as information. The time-length of this duration when the return signals are recorded is called the width of the range detection window, W. In the absence of an adequately responsive range tracker, this width, W, should be wide enough to accommodate all return signals in the form of waveforms from rough terrain. Otherwise, the return signal from the tip of a mountain, say, will arrive too early and the return signal from a deep trench will arrive too late to be located inside this range detection window. As the obvious consequence, the elevations and locations of the mountain top and deep trench will not be known. However, the width of this range detection window cannot be so wide that return signals from locations far away from radar nadir can find their way back to the recorder. Therefore, a proper terrain profiling radar system should have a range detection window wide enough for recording wanted return signals and narrow enough to exclude unwanted return signals. The compromise, sometimes, can be found by having an adequately responsive range tracker. In the absence of a range tracker, the maximum elevation change $(\Delta h)_{max}$ in the unit of meters on the ground surface can be obtained as

$$(\Delta h)_{max} = 0.15W \qquad (4)$$

where W is in units of nanoseconds and is the product of range resolution in time and number of range resolution cells in a radar sweep.

5. Range Tracker Rate

When the antenna-to-ground surface distance is different from what can be detected by the range detection window, the return signal from the ground can not be detected and recorded. Once this situation occurs the radar receiver circuitry should change its codes to relocate its range detection window. The new position, in reference to time delay from the time the signal was transmitted, of the range detection window depends on when the return signal is received. The rate of change in codes in time delay per unit time (usually, in unit of nanoseconds per nanosecond) is called range tracker rate, R. The quotient of this range tracker rate to radar platform speed $|v|$, in unit of meters per second, gives a restriction on the maximum detectable elevation change per unit distance $(\Delta h/\Delta x)_{max}$ by the range tracker as

$$(\Delta h/\Delta x)_{max} = 0.15 \times 10^9 \, R/|\vec{v}| \qquad (5)$$

where Δh is the elevation difference, Δx is the distance along the ground track, R is in unit of nanoseconds per nanosecond, and $|\vec{v}|$ is in unit of meters per second.

III. 10 GHZ CW PRN CODED NANOSECOND RADAR SYSTEM

The NRL 10 GHz CW PRN coded nanosecond radar generates a continuous train of sinusoidal electromagnetic waves. The phase of this continuous wave is shifted by 180° whenever the internal code changes. The length of time (usually 1, 2, 4, or 10 nanoseconds) this code remains unchanged can be interpreted as the pulse duration of a pulse radar and is directly related to radar's ability in range resolution. With each range resolution there is a definite dimension of radar footprint, circular shaped of radius, r, at the ground surface. The radar antenna beamwidth is 7°. The data acquisition system has a variable scan rate, from 1 to 99 KHz, for acquiring data to construct return waveforms. The width of the return waveform can be a sweep of 64, 128, or 256 range cells. The number of returns averaged can be from one to any even number up to 16.

IV. FLIGHT EXPERIMENT

An airborne experiment was conducted on 11 December 1978 using Naval Research Laboratory's RP-3A Orion research aircraft. This aircraft carried a X-band nanosecond radar and a pulse laser profilometer together with a LTN-72 Inertial Navigation System (INS) manufactured by Litton Industry. The RP-3A was flown straight ahead at the altitudes of around 300 meters over several places in the states of Mississippi, Tennessee, and Virginia with both radar and pulse laser profilometer operating simultaneously. The INS provided information on position (latitude and longitude), heading, track angle, and air speed while a pressure altimeter provided the approximate altitude of the aircraft. The distance from radar antenna, located at the belly of the RP-3A, to the ground surface was provided by the pulse laser profilometer measurements. Pitch, roll, and vertical acceleration of the aircraft motions were provided by the laser instrument box.

Among the many data runs taken during that day, one particular track over Marshall County, Mississippi, right next to the Tennessee border was demonstrated to be a typical data set for our purpose, the investigation of the use of X-band nanosecond airborne radar for terrain profiling. The track started at 34°57'36" north latitude and 89°26'6" west longitude, and stopped at 34°57'28.8" north latitude and 89°22'19.2" west longitude. It took 1 minute and 11 seconds, from 1:21:9 p.m. to 1:22:20 p.m. central time, to run the whole course of this straight track over moderately rough terrain populated with tall trees. The data set taken for this track only is presented in this report.

V. PHYSICAL AND SYSTEM PARAMETERS

1. Radar System Parameters:

The radar system parameters used in the experiment are listed in the following:

Range Resolution, τ : 4 nanoseconds

Scan Rate: 20 KHz

Number of Range Resolution Cells in Waveform: 128

Number of Returns Averages, n: 2

Width of Range Detection Window, W: 512 (= 4 x 128) nanoseconds

Range Tracker Rate, R: 0 nanoseconds per nanosecond

With mean aircraft speed, $|\vec{v}|$, at 83.63 meters per second and aircraft altitude, H, at 275 meters, other radar system parameters can be calculated from radar system parameters used in the experiment as:

Range Resolution in Length, $C\tau/2$: 0.6 meters

Footprint Radius, r: 16.50 meters

Equivalent Repetition Rate, p (scan rate/number of range resolution cells): 156.25 Hz

Basic Sampling Distance, Δs, given by Equation (2): 0.535 meters

Sampling Distance, s, given by Equation (3): 1.07 meters

Width of Range Detection Window, $(\Delta h)_{max}$, given by Equation (4): 76.8 meters

2. Laser System Parameters:

The pulse repetition rate, p_L, for the laser was 96.74 Hz. With the mean aircraft speed, $|\vec{v}|$, at 83.63 meters per second, the sampling distance, s_L, of the laser with this pulse repetition rate should be 0.86 meters. Since the laser beam width was 1.5 milliradians, laser footprint radius was 0.21 meters from the altitude of 275 meters. At this altitude, the nominal range resolution of the laser system was 0.15 meters measured by internal electronic circuitry on the delay time between the leading edges of the emitted and the return pulses.

VI. DATA ANALYSIS

Several data analysis options have been considered. These options were performed with and without a high pass filter and with and without the removal of aircraft motions whose effects on range measurement were in a frequency band lower than those caused by terrain elevation changes. Furthermore, a performance model for the operation of the radar range threshold tracker on the return waveform has to be selected for the determination of range to the ground surface. In addition, because of the dimension of the equivalent half beam-width of the radar was many times larger than that of the half beam-width of the laser, a smoothing filter would have to be applied to the laser data as well in order to make a meaningful intercomparison between measurements made by radar and laser.

1. Aircraft Motions Removal:

In general, aircraft motions have six degrees of freedom in three mutually independent directions. They are three displacements:

along-track, cross-heading, and heave; and three rotations: roll, pitch and yaw. Since the INS had three mutually perpendicular gyros, aircraft motions in all six degrees of freedom were sensed and subsequently recorded. Aircraft motions in both along-track and cross-track directions can be calculated from recorded ground speed, track angle, and heading so that the location of aircraft in latitude and longitude can be pinpointed precisely. Aircraft heave motion was recorded by a vertical accelerometer as vertical acceleration. Theoretically this heave motion can be obtained by integrating this vertical acceleration. Yaw motion was the difference between track angle and heading. Roll and pitch motions were recorded as what they were. The combined effects of roll, pitch, and yaw were two; one, measurement footprint was not necessarily at nadir and two, in so doing, nadir range measurements were slant range measurements. Since both roll and pitch were small and their periods were long and the yaw was steady, these two effects were neglected. If a high pass filter is used on the data, the additional range included in slant range measurement can be at least partly removed to approximate the measurement in the required nadir direction.

Since aircraft heave motions have the greatest effect on range measurement, the removal of this effect in some applications is absolutely necessary. For example, if the terrain profile in reference to an arbitrary datum point is desirable, the removal of aircraft heave motion is necessary. However, if the range from aircraft to ground surface is desired, there is no need to remove this motion effect at all.

Because there was a drift in the vertical accelerometer system, a proper integration from vertical acceleration record to vertical displacement profile requires three intergration constants. These three integration constants could be obtained by having three sites of known elevations whose locations are well separated in distance under aircraft track. Since this condition could not be satisfied by the experimental arrangements, an alternative for this condition was admitted with the assumption that the mean elevation of terrain profile over a long track is zero. For a short track, this assumption is not valid.

2. High Pass Filter:

The purpose of using a high pass filter is to remove from the range measurements those components which have lower frequencies than a predetermined frequency. For example, if there is a clear separation of frequencies between those of aircraft motions and those of the terrain profile, it is possible to use a high pass filter to remove the effects of aircraft motions, usually of lower frequencies, from the range measurements. If these two frequency bands overlap, the effects of aircraft motions on the range measurements cannot be removed entirely by high pass-filtering technique.

3. Radar Range Threshold Tracker

Within the radar range detection window, there were 128 range cells of 4 nanoseconds each. Each cell represented a range increment of 0.6 meters. The range cell that detects the first radar energy reflected from the surface is called the leading edge cell of the return waveform. Gradually more and more energy comes back and its intensity grows. At one of the

subsequent range cells the intensity of return energy actually drops. The intensity of the return energy is peaked at the preceding range cell. The portion of return waveform between the leading edge and the peak is called the rise portion of the return waveform and the portion of return waveform after peak is called the plateau portion of the return waveform. The intensity of return energy at the plateau portion eventually will reduce to zero. For a nadir looking radar antenna, the return energy is due to specular scattering. Over land, this return waveform is very narrow indeed (Horan and Choy, 1984) because the returned signal comes from the ground surface near nadir.

Ideally speaking the total time delay to the leading edge of return waveform should be used for the calculation of radar range. However, signals reflected from tall subjects such as trees located within radar footprint may arrive earlier than the signal returned from nadir. The leading edge portion of the waveforms show, in this case, an erratic fluctuation in energy intensity at an overall low level but sustained continuously over several range cells. The range cell of the leading edge, does not correspond to radar nadir range to the ground surface. One has to locate the rise portion of waveform and then determine the real leading edge among the leading edge portion of the waveform.

4. Smoothing Filter

The equivalent half beam-width of the radar signal is usually many times larger than the half beam-width of the laser pulse. A smoothing filter would have to be used on the laser data so that the half beam-width of both radar signals and laser pulses can be approximately equal. This step in data analysis is necessary for making a meaningful inter-comparison of range measurements between those made by radar and laser systems.

VII. RESULTS

Figure 1 shows both laser and radar profile measurements as function of time in seconds; no high pass filter was used, no aircraft motions removal algorithm was used, laser data was smoothed by an 11 point filter, and the radar range threshold tracker was activitated at a radar energy intensity level of 50 out of 1024 counts (10 bits). The horizontal scale can be converted to distance along track by a factor of 83.63 meters to a second. These two profiles are quite similar except that laser profile still obviously shows the presence of trees. The values of ordinates for laser and radar ranges are not the same because the preset delay times for laser and radar were different and resulted in a total difference in range of 332 meters. Please notice that the vertical scale for both laser and radar range measurements are the same for measurement of relative topography. Since there were no aircraft motions removal, the range measurements presented in Figure 1 are aircraft altitudes above the ground surface. Figure 2 shows both laser and radar profile measurements as those shown in Figure 1 except that an algorithm for the removal of aircraft motion was used. The algorithm assumes that, over the whole track, the mean excursion of profiles from the mean profile is zero. Because laser data still contain information from trees, the laser profile measurements have an additional range offset of 1.5 to 2 meters from the profile detected by radar. Figure 3 shows both laser and radar profile measurements as those shown in Figure 1

except, this time, a high pass filter was used on both the laser and radar range data set. Both profiles are quite similar and the high frequency information regarding, trees dissappears from the laser profile.

In comparing the profiles shown in Figure 3 with those shown in Figure 1 and 2, the general trends of laser and radar profiles, shown in Figure 3, follow closer to the general trends of those profiles shown in Figure 1 than those in Figure 2. Theoretically speaking, it should be the other way around. The only explanation for this fact is that the assumption used in aircraft motion removal algorithm as a replacement for the three required integration constants is not valid for this short track of 7500 meters in total length.

Figure 4 shows laser and radar range measurements after both high pass filter and aircraft motion removal algorithm were used. Comparing with radar profile measurements the laser profile measurements show higher frequency variations. These high frequency variations are similar to those found in the laser measurements in Figure 3. The general trends of the profiles follow closely to those of the profiles shown in Figure 2. This type of similarity existed among profiles shown in Figures 2 and 4 indicates that the aircraft motion removal algorithm has a dominant influence on final product of profile measurements.

Terrain profiling requires proper reference of the profile to a known datum. This requirement can only be satisfied by having at least three known ground elevations whose locations are well separated in distance along track so that the effects due to vertical aircraft motion as a function of flight time can be properly removed from radar range measurement. In some of the applications, when the distance from radar antenna to the ground surface is the only required information, there is no need to remove the vertical aircraft motion. Under these circumstances, there is also no need to know three ground elevations along the track at all.

In any event, radar profiles shown in Figures 1-4 demonstrate radar's capability to provide similar terrain profiles to those given by laser profilometer except:

1. Radar-sensed terrain profiles did not contain information on the existence of forest at places laser-sensed terrain profiles indicated.

2. At places where there were large foreside range slopes, exemplified by the large foreside range slope of 19.5 m/173 m (or 19.5 m/2 sec) between 29th to 31st seconds of the profiles shown in Figure 1, radar lost its range lock and could not resolve range at all. This foreside range slope of 9.75m per second of flight time seems to be the limit of radar's range tracking circuitry. In other words, if foreside range slope equals or exceeds 9.75m/sec, the radar system used cannot resolve range. However, in the case of aftside, this limit on range slopes was higher.

One of the consequences derived from the first exception is that radar system used cannot detect narrow and tall objects, such as tall trees or power poles above ground surface, due to radar's large footprint. For extremely low flying aircrafts, the lack of information from its radar of narrow and tall objects above ground surface ahead presents great danger to

the safety of this aircraft. In some of the detailed analysis of radar return waveform, there is a slight hint that some of the tree tops were observed but its assertion requires further investigation. Nevertheless, a range resolution finer than 4 nanoseconds and a better waveform analysis algorithm for identifying tops of narrow and tall objects in addition to ground surface are going to increase the terain profiling capability of airborne radar system.

Plots of the radar range slope functions are clearly required for demonstrating the second exception. Figure 5 presents such a function for the radar range profile shown in Figure 1. The horizontal axis is the radar range slope, in units of multiples of 0.0408, i.e., each unit stands for 0.0408 meters elevation change per meter in distance along the flight track. Positive units stand for foreside range slope and negative units stand for aftside range slope. The vertical axis is the number of occurences of this radar range slope. It is quite obvious, from Figure 5, that this radar slope density function is skewed toward aftside range slope because the limit at which radar range tracking circuitry losses its lock is higher for aftside range slopes than that for foreside range slopes, as stated in the second exception. The ground truth provided by the laser range slope density function in Figure 6, indicates however that the distribution of this function is symmetrical and has wider width than that of the radar range slope density function. Because the radar has a larger footprint, its range slope density function should have narrower distribution.

Figures 7 and 8 show the radar and the laser range slope density functions, respectively, for Figure 4. In this case, both high pass filter and aircraft motion removal algorithm were applied to the radar and laser profile data, no significant difference among these two functions can be observed. The bimodel distributions close to the peaks of both of these functions must be the results of numerical artifact and should be ignored. The distributions of these two functions are quite similar in shape and exhibit the characteristic of narrow distribution as the result of high pass filtering.

VIII. CONCLUSION

In summary, several points can be made regarding the use of X-band CW nanosecond airborne radar for terrain profiling:

1. Under the condition of comparable sampling intervals, the terrain profile sensed by radar is almost the same as that sensed by the laser profilometer except radar sensed profile does not contain information of narrow and tall objects above the ground surface.

2. A radar range resolution finer than 4 nanoseconds and a better algorithm on return waveform analysis for identifying narrow and tall objects in addition to the ground surface are going to improve accuracy and precision of radar's capability in terrain profiling.

3. For a short flight track, the removal of the effects on radar range measurements due to aircraft motion cannot be achieved without knowing three ground surface elevations whose locations are well separated along the flight track.

4. The limit at which radar range tracking circuitry loses its lock and, thus, its ability in resolving range is higher for aftside range slopes than for foreside range slopes.

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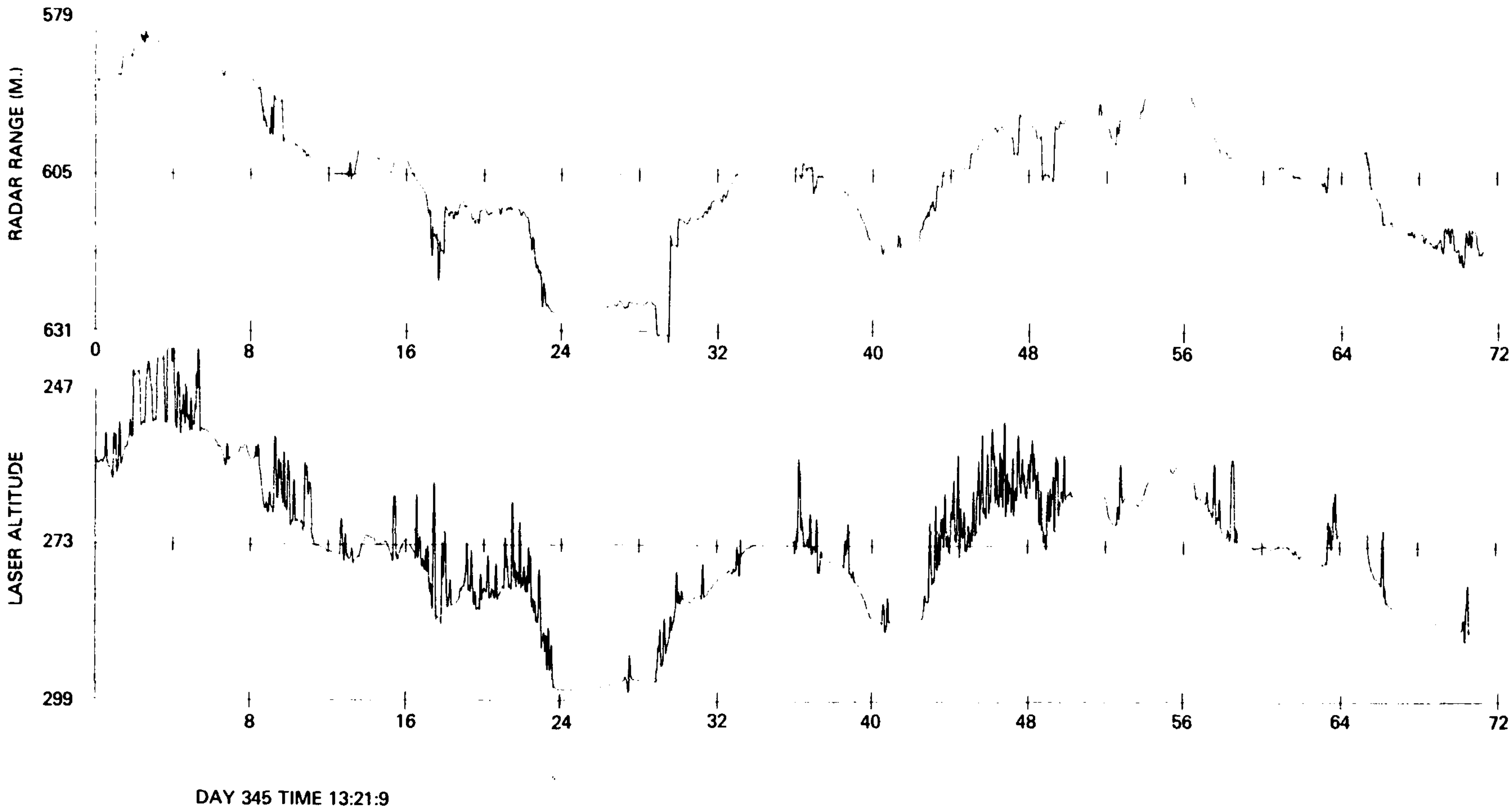

Figure 1 – Laser and radar profile measurements with respect to time in seconds; no high pass filter used, no aircraft motion removal algorithm used, laser data smoothed with 11 points smoothing filter, and radar range threshold tracker at 50 counts.

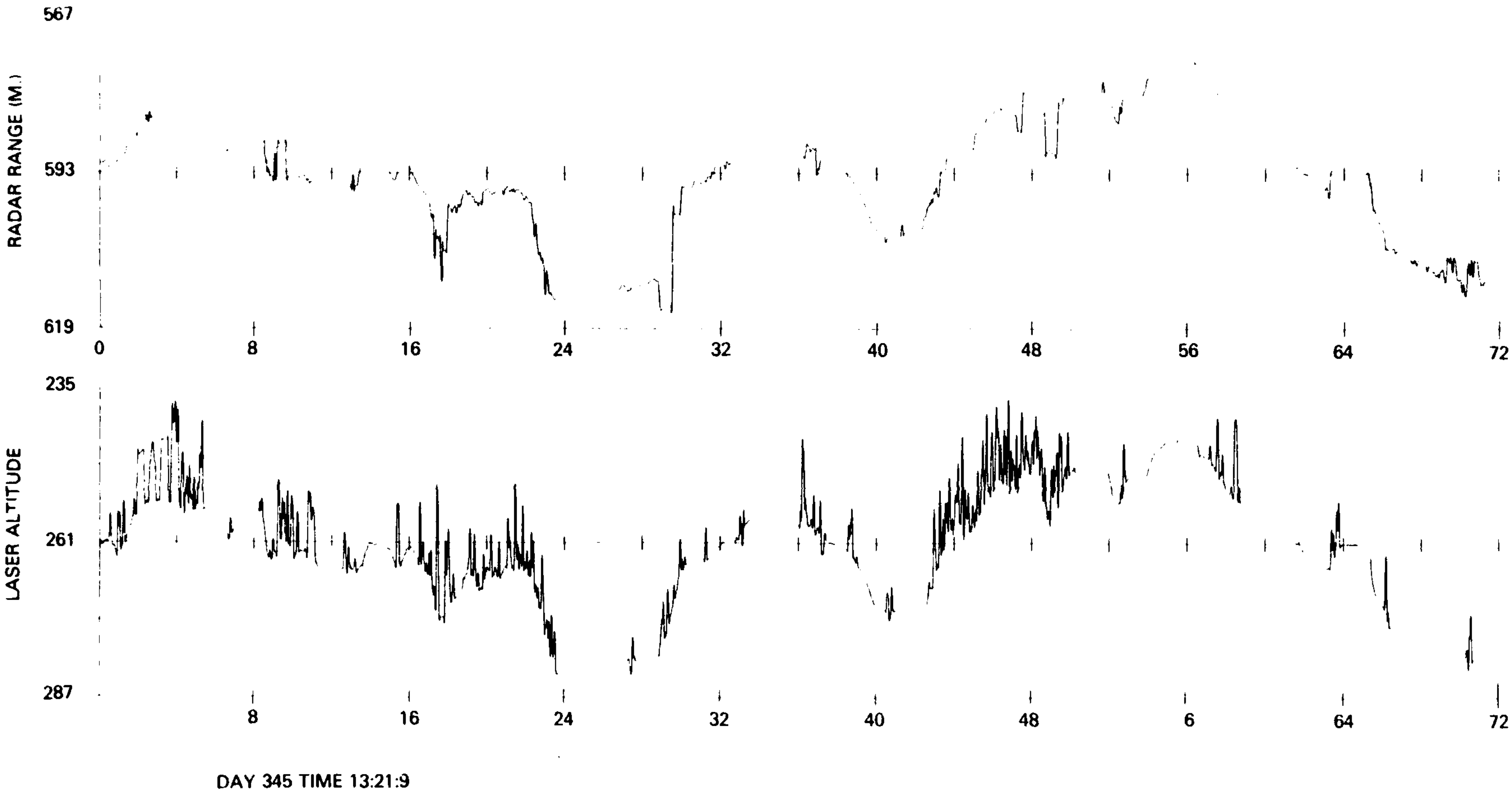

Figure 2 - Laser and radar profile measurements with respect to time in seconds; no high pass filter used, aircraft motion removal algorithm used, laser data smoothed with 11 points smoothing filter, and radar range threshold tracker at 50 counts.

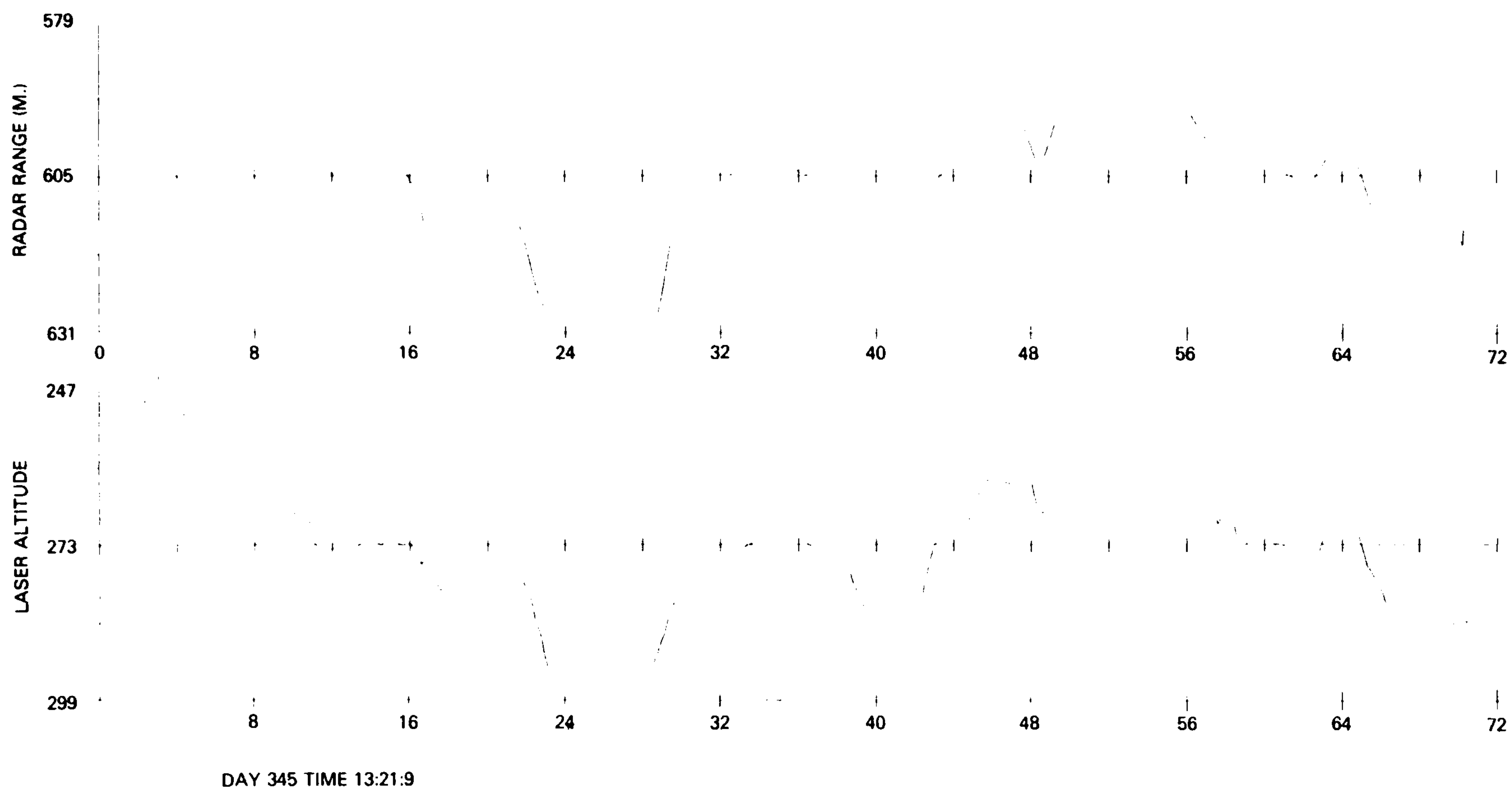

Figure 3 - Laser and radar profile measurements with respect to time in seconds; high pass filter used, no aircraft motion removal algorithm used, laser data smoothed with 11 points smoothing filter, and radar range threshold tracker at 50 counts.

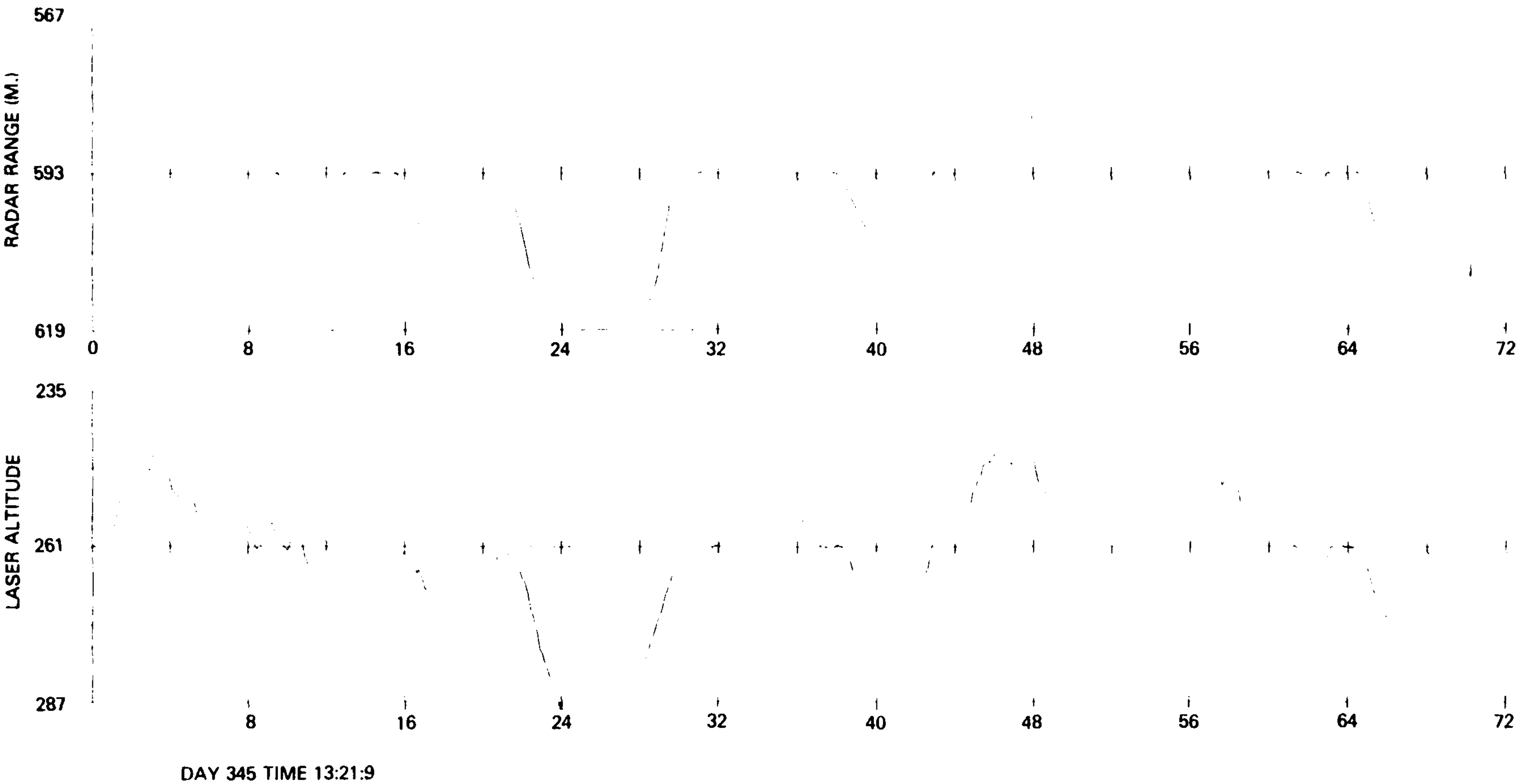

Figure 4 - Laser and radar profile measurements with respect to time in seconds; high pass filter used, aircraft motion removal algorithm used, laser data smoothed with 11 points smoothing filter, and radar range threshold tracker at 50 counts.

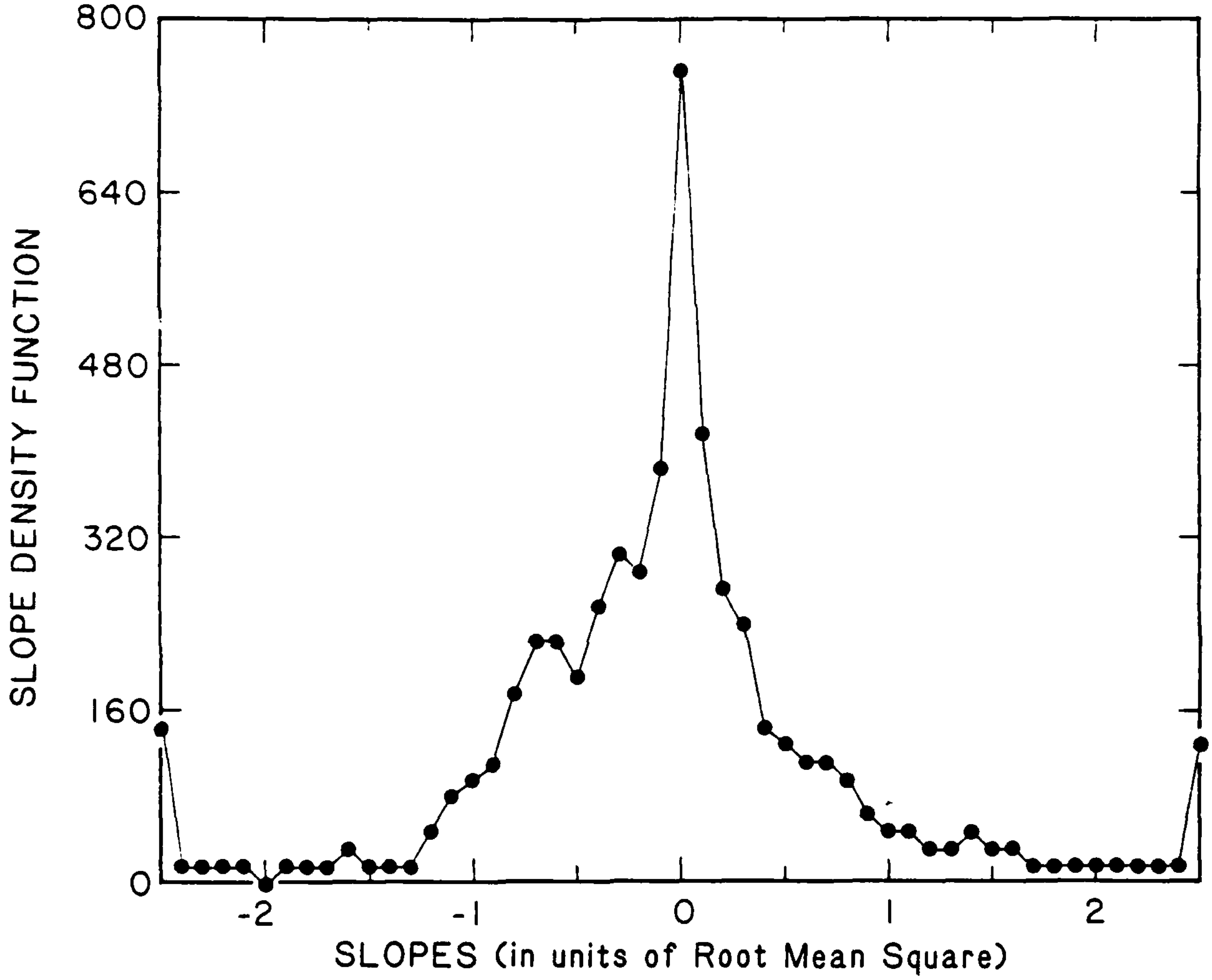

Figure 5 - Radar range slope density function for profile shown in Figure 1. Horizontal axis is range slope in unit of 0.0408.

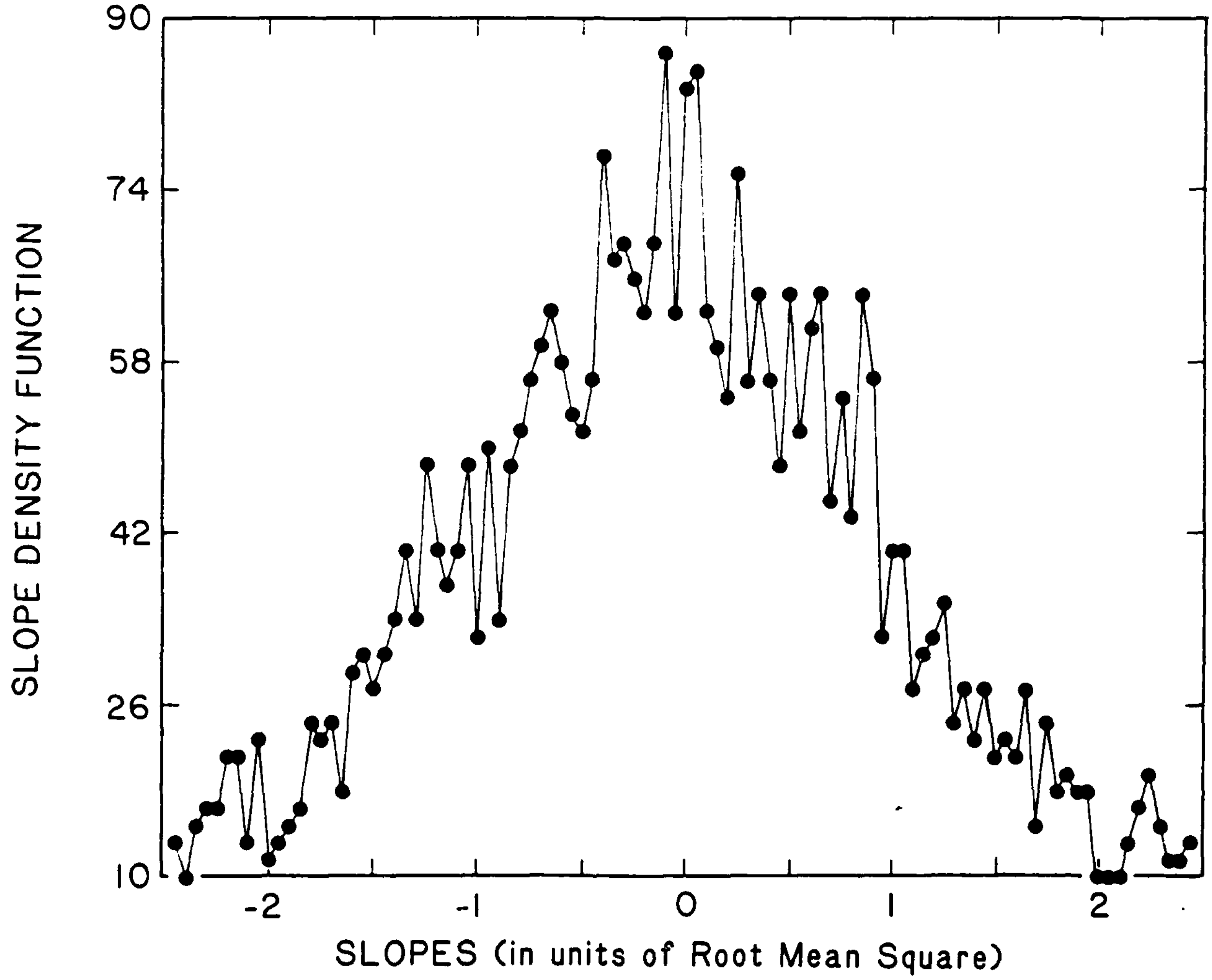

Figure 6 - Laser range slope density function for profile shown in Figure 1. Horizontal axis is range slope in unit of 0.0391.

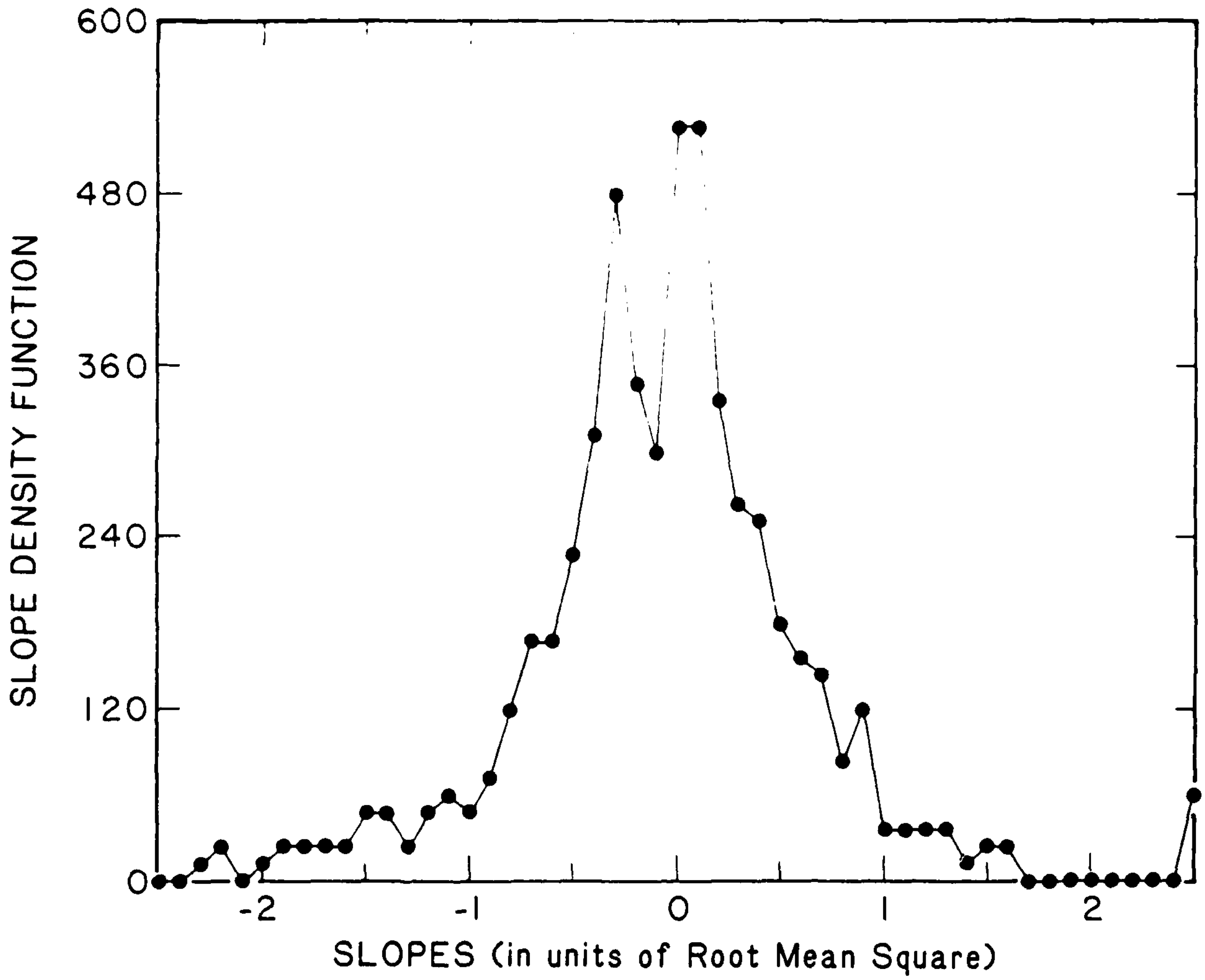

Figure 7 - Radar range slope density function for profile shown in Figure 4. Horizontal axis is range slope in unit of 0.0381.

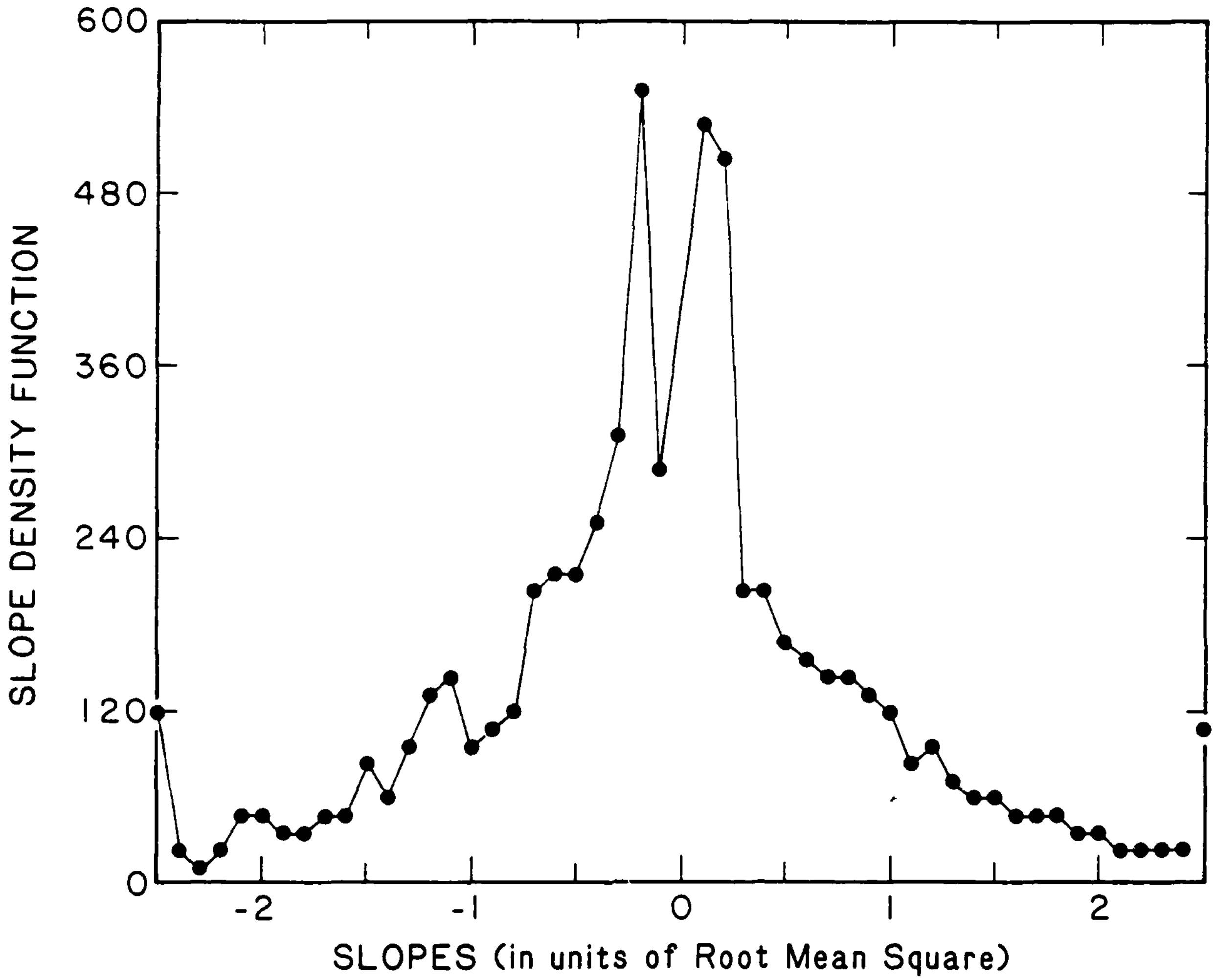

Figure 8 - Laser range slope density function for profile shown in Figure 4. Horizontal axis is range slope in unit of 0.0347.

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